Bulletin of the Seismological Society of America

VOL. 27 JULY, 1937 No. 3

MATERIALS FOR THE STUDY OF DEEP-FOCUS EARTHQUAKES*

(SECOND PAPER)

By B. GUTENBERG and C. F. RICHTER

INTRODUCTION

THE PRESENT PAPER is supplementary to a previous publication under the same title,[1] for which a list of errata is here given.[2] The first paper has been translated into French by Professor E. Rothé, and is to be published by the Bureau Central Séismologique International. (The French publication will contain a travel-time chart for focal depth 600 km. in place of that for 400 km. given in the English paper.) At the request of Professor Rothé a more detailed account of the calculation of certain travel times was drawn up, which he has also translated, and which will appear as an additional note in the French publication. This additional note is given in English in the present paper. To this are added a new table (table 1, pp. 161-165 below) giving epicentral distance as a function of the travel time of P and of the focal depth, and a further discussion of methods for locating the epicenters of deep shocks.

CALCULATION OF TIMES FOR pP, sS, sP, pS

In figure 1 let G be the hypocenter of a shock at depth A for which the travel times of P and S are known; in particular, this may be a normal shock, with A assumed as 25 km. Let H be another hypocenter at depth B (which may be 100, 200, 300 . . . km.), and consider a ray passing through both G and H. For the hypocenter H the time along this ray to a distant station will be decreased by

* Manuscript received for publication May 17, 1937.

[1] B. Gutenberg and C. F. Richter, "Materials for the Study of Deep-Focus Earthquakes," *Bull. Seism. Soc. Am.*, 26:341-390 (1936).

[2] Errata in the previous paper:

P. 351, table 8, 70°, 700 km., *for* 11:26 *read* 12:26.
P. 361, table 22, 105°, 300 km., *for* 37:21 *read* 27:21.
P. 368, table 36, 65° and 70°; all six minutes *given as* 48 *should read* 47.
P. 370, table 40, 65°, 500 km., *for* 19:47 *read* 18:47.
P. 377, table 46, heading, read $0=(pP+P)/2-t_p-c$.
P. 377, table 46, 80°, 700 km., *for* 5 *read* 4.
P. 379, table 48, 2:15, 90°, *for* 603 *read* 630.
P. 383, table 51, Bombay, minute of S; *for* 8 *read* 7.
P. 383, table 51, Manila, minute of S; *for* 14 *read* 15.
P. 384, table 51, column heading; *for* 36^d 10^h 38^m *read* 836^d 10^h 38^m.

the time along GH, while the distance will be decreased by DE (D, E being the epicenters corresponding to G, H). The time from G to H is $\int_A^B \frac{dr}{v \cos i}$, and DE is $\int_A^B \frac{\tan i}{r}\, dr$. That is, if for the depth A we have travel-time t at distance Δ, then for depth B we have time $t - \int_A^B \frac{dr}{v \cos i}$ at distance $\Delta - \int_A^B \frac{\tan i}{r}\, dr$. By varying the assumptions (initial angle of incidence; or, better, the initial epicentral dis-

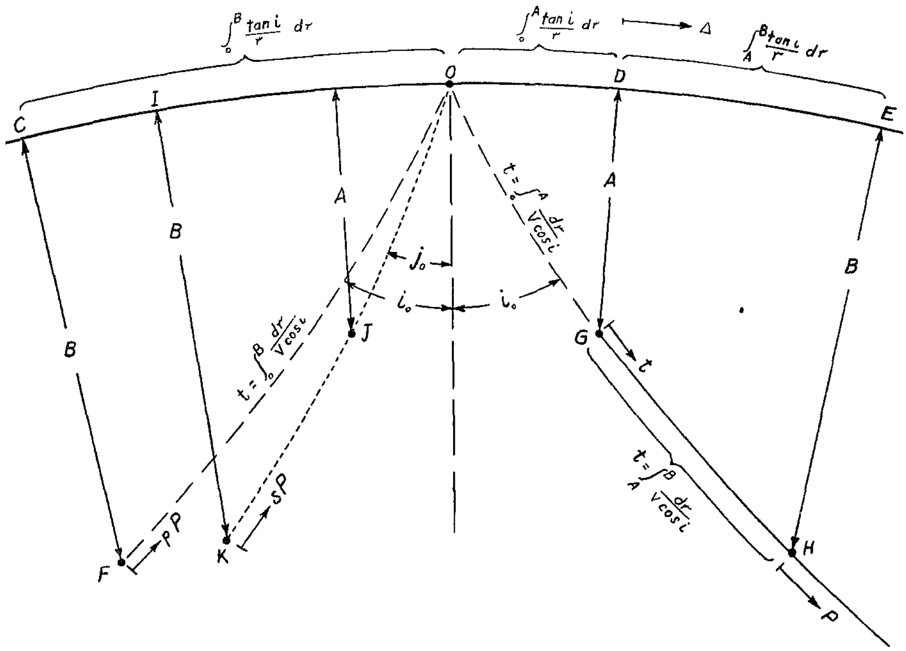

Fig. 1.

tance at G) the whole curve for depth B can be constructed without the necessity of any approximation.

The figure shows that the times for pP may be derived by a similar process. If the hypocenter F is at depth B, the path of pP is FOGH, so that the travel time of pP originating at F is equal to that of P originating at G plus the times along FO and OG; and the corresponding distance is that of G increased by CO and OD. The time along FO + OG is $\int_0^B \frac{dr}{v \cos i} + \int_0^A \frac{dr}{v \cos i}$, and CO + OD =

$\int_0^B \frac{\tan i}{r}\,dr + \int_0^A \frac{\tan i}{r}\,dr$. Hence if for depth A we have the travel time of P at distance Δ, then at depth B we have the travel time for pP

$$t+\int_0^B \frac{dr}{v\cos i}+\int_0^A \frac{dr}{v\cos i}\text{ at distance }\Delta+\int_0^B \frac{\tan i}{r}\,dr+\int_0^A \frac{\tan i}{r}\,dr.$$

This is the result stated in the first paper, and again no approximation is involved.

The procedure for S and sS is exactly analogous to that for P and pP. For sP and pS it is more complicated, and is best explained in connection with a particular example.

Suppose that we wish to derive times for a focal depth of 300 km. from those for a normal shock at $\Delta = 45°$. Table 5 of "On Seismic Waves I"[3] gives the travel time of P in this case as $8^m\,20^s$. The corresponding time for S is given in table 19, "On Seismic Waves, II," as $14^m\,54^s$. The quantity $\frac{1}{v_{40}}$ is .0726 for P and 0.127 for S (tables 16 and 20, "On Seismic Waves, II").

The corrections to time and distance required to pass to the case of 300-km. focal depth are taken from tables 1, 2, 3, and 4 of the first paper (1936). The results are:

	Distance (degrees)	Time (min.: sec.)
P for normal shock	45.0	8:20
Correction GH (tables 1*a*, 2*a*)	−1.9	−0:43
P for depth 300 km	43.1	7:37
P for normal shock	45.0	8:20
Correction GOF (tables 1*b*, 2*b*)	2.1	0:52
pP for depth 300 km	47.1	9:12
S for normal shock	45.0	14:54
Correction GH (tables 3*a*, 4*a*)	−1 8	−1:15
S for depth 300 km	43.2	13:39
S for normal shock	45.0	14:54
Correction GOF (tables 3*b*, 4*b*)	2.1	1:32
sS for depth 300 km	47.1	16:26

[3] B. Gutenberg and C. F. Richter, "On Seismic Waves," *Gerlands Beitr. z. Geophys.*, 43:56-133 (1934); second paper, *ibid.*, 45:280-360 (1935).

To derive times for sP, consider the hypocenter K at depth B. The wave is transverse on the path KO and longitudinal on the path OG. Take a point J at depth A on KO. Let w be the velocity of transverse waves, v that of longitudinal waves; w_0 and v_0 are their values at the surface, $\overline{w}$ and $\overline{v}$ are apparent velocities. Let j_0 be the angle of incidence of the ray KO at the surface, i_0 being that of OG. Then $\frac{\sin j_0}{\sin i_0} = \frac{w_0}{v_0}$. At any depth along a given ray $\overline{v} = \frac{v_0}{\sin i_0}$, $\overline{w} = \frac{w_0}{\sin j_0}$. Hence $\overline{w}$ for KO equals $\overline{v}$ for OG.

It follows that in computing for sP we use throughout the apparent velocity of the longitudinal ray through G and H, and for pS we use that of the corresponding transverse ray; in our example these are the reciprocals of 0.0726 and 0.127, respectively. For sP

	Distance (degrees)	Time (min.: sec.)
P for normal shock	45.0	8:20
Correction GO (tables 1a, 2a, h=0)	0.1	0:05
Correction OJ (tables 3a, 4a, h=0)	0.1	0:07
Correction JK (tables 3a, 4a, h=300)	0.8	1:05
sP for depth 300 km	46.0	9:37

If with these data we try to calculate a corresponding point for pS, we find that in tables 1 and 2 (of the first paper: 1936), which should give the last two corrections, there is no entry for the required reciprocal apparent velocity, 0.127. pS does not exist for the given distance and depth. (Cf. table 16.)

An example for pS may be obtained by calculation for a distance of 90° and focal depth 300 km. We have $\frac{1}{\overline{v}_{40}} = 0.091$.

	Distance (degrees)	Time (min.: sec.)
S for normal shock	90.0	23:54
Correction, tables 3a, 4a, h=0	0.1	0:08
Correction, tables 1a, 2a, h=0	0.1	0:05
Correction, tables 1a, 2a, h=300	3.0	0:52
pS for depth 300 km	93.2	24:59

Individual results obtained by such calculation will often differ by a few seconds from those tabulated in the paper, which are based on smoothed curves corresponding to tables 1 to 4 (1936) and have then been subjected to further smoothing by means of table 5 (1936).

TABLE 1

EPICENTRAL DISTANCES FOR GIVEN TRAVEL TIMES OF P AND GIVEN FOCAL DEPTH

P–O (min.: sec.)	Focal depth in km.								
	25	100	200	300	400	500	600	700	800
0:30	1.7	2.0	0.9						
35	2.0	2.4	1.7						
40	2.4	2.7	2.2	0.6					
45	2.8	3.1	2.6	1.7					
50	3.1	3.5	3.0	2.4	0.0				
55	3.5	3.9	3.4	2 9	1.7				
1:00	3.8	4.3	3.8	3.4	2.7				
05	4.1	4.7	4.2	3.8	3.3	1.9			
10	4.5	5.1	4 6	4.3	3.8	2.9			
15	4.8	5.4	5.0	4.7	4.3	3.7	2.0		
20	5.2	5.8	5.4	5.1	4.9	4.4	3.1	0.0	
25	5.6	6.0	5.8	5.6	5.4	5.1	4.0	2.2	
30	5.9	6.3	6.2	6.0	5.9	5.6	4.8	3.5	1.1
35	6.3	6.7	6 6	6.5	6.4	6.1	5.4	4.4	3.0
40	6.6	7.0	7 0	6.9	6.8	6.6	6.0	5.0	4.0
45	7.0	7.3	7.4	7.3	7.3	7.1	6.5	5.7	4.8
50	7.3	7.7	7.8	7.7	7.7	7.6	7.0	6.3	5.6
55	7.7	8.1	8 1	8.1	8.2	8.1	7.5	7.0	6.3
2:00	8.1	8.5	8.5	8.5	8.7	8.6	8.1	7.6	7.0
05	8.4	8.8	8 9	8.9	9.1	9.1	8.6	8.2	7.8
10	8.7	9.2	9.3	9.4	9.5	9.5	9.2	8.8	8.5
15	9.1	9.6	9.6	9.8	9.9	9 9	9.7	9.4	9.1
20	9.5	9.9	10.0	10.2	10.3	10.3	10.2	10.0	9.8
25	9.9	10.3	10.4	10.6	10.7	10.8	10.7	10.6	10.4
30	10.2	10.6	10.7	11.0	11.1	11 2	11.2	11.2	11.0
35	10.6	11.0	11.1	11.4	11.6	11 7	11.7	11.7	11.5
40	10.9	11.4	11.5	11.8	12.1	12.2	12.2	12.2	12 0
45	11.2	11.7	11.9	12.2	12.5	12.7	12.7	12.7	12.6
50	11.6	12.0	12 3	12.6	12.9	13.1	13.2	13.2	13.1
55	12.0	12.4	12.7	13.0	13.4	13.6	13.7	13.7	13 6
3:00	12.3	12.8	13 1	13.4	13.8	14.0	14.1	14.2	14.1
05	12.7	13.2	13.5	13.8	14 2	14.4	14 5	14.7	14.6
10	13.1	13.6	13 8	14.2	14.6	14.9	15.0	15 2	15.1
15	13.4	13.9	14.2	14.5	15.1	15.4	15.5	15.7	15.6

TABLE 1—(*Continued*)

P–O (min.: sec.)	Focal depth in km.								
	25	100	200	300	400	500	600	700	800
3:20	13.8	14.3	14.6	15.0	15.5	15.8	15.9	16.2	16.2
25	14.2	14.6	15.0	15.4	16.0	16.3	16.5	16.7	16.8
30	14.6	15.0	15.4	15.8	16.4	16.7	17.0	17.2	17.2
35	15.0	15.4	15.8	16.2	16.8	17.2	17.5	17.8	18.0
40	15.3	15.8	16.2	16.7	17.3	17.7	18.1	18.3	18.6
45	15.7	16.2	16.6	17.1	17.7	18.2	18.6	18.9	19.1
50	16.1	16.6	17.1	17.6	18.2	18.7	19.2	19.5	19.7
55	16.5	17.0	17.5	18.1	18.7	19.2	19.7	20.0	20.3
4:00	16.9	17.4	18.0	18.6	19.2	19.7	20.2	20.6	20.9
05	17.3	17.8	18.5	19.1	19.7	20.2	20.7	21.1	21.4
10	17.8	18.3	19.0	19.6	20.2	20.8	21.3	21.7	22.0
15	18.2	18.8	19.4	20.0	20.7	21.3	21.9	22.2	22.5
20	18.6	19.2	19.8	20.5	21.2	21.8	22.4	22.8	23.1
25	19.1	19.6	20.3	21.0	21.7	22.3	22.9	23.4	23.7
30	19.5	20.0	20.8	21.5	22.2	22.8	23.5	24.0	24.3
35	20.0	20.5	21.3	22.1	22.8	23.4	24.1	24.5	24.9
40	20.5	21.0	21.8	22.6	23.4	24.0	24.7	25.1	25.5
45	20.9	21.4	22.2	23.1	24.0	24.6	25.3	25.7	26.1
50	21.4	21.9	22.7	23.6	24.5	25.2	25.9	26.3	26.6
55	21.8	22.5	23.3	24.2	25.1	25.9	26.4	26.9	27.2
5:00	22.3	23.0	23.8	24.7	25.6	26.5	27.1	27.5	27.8
05	22.8	23.5	24.4	25.3	26.2	27.0	27.6	28.1	28.4
10	23.3	24.0	24.9	25.9	26.8	27.6	28.2	28.7	29.0
15	23.8	24.5	25.5	26.5	27.4	28.2	28.8	29.3	29.6
20	24.3	25.0	26.0	27.1	28.0	28.8	29.4	29.9	30.2
25	24.8	25.6	26.6	27.7	28.6	29.4	30.0	30.4	30.8
30	25.3	26.1	27.2	28.3	29.2	30.0	30.6	31.0	31.3
35	25.9	26.7	27.8	28.8	29.7	30.5	31.2	31.6	31.9
40	26.4	27.2	28.3	29.4	30.3	31.1	31.7	32.1	32.5
45	27.0	27.7	28.8	29.9	30.9	31.7	32.3	32.7	33.1
50	27.5	28.2	29.4	30.5	31.5	32.3	32.9	33.3	33.7
55	28.1	28.8	29.9	31.0	32.1	32.9	33.5	34.0	34.3
6:00	28.7	29.3	30.5	31.6	32.7	33.5	34.1	34.5	34.9
05	29.3	29.9	31.1	32.2	33.3	34.1	34.7	35.1	35.5
10	29.9	30.5	31.7	32.8	33.9	34.6	35.2	35.7	36.1
15	30.4	31.1	32.3	33.4	34.5	35.2	35.8	36.3	36.7

TABLE 1—(*Continued*)

P—O (min.: sec.)	Focal depth in km.								
	25	100	200	300	400	500	600	700	800
6:20	30.9	31.7	32.9	34.0	35 1	35 8	36.4	36 9	37.4
25	31 7	32.3	33.4	34.6	35.7	36.4	37.0	37.6	38.2
30	32 2	32.9	34.0	35.2	36.3	36.9	37 6	38.3	38.9
35	32 8	33.5	34.7	35 8	36.9	37.5	38.2	38 9	39 6
40	33.3	34.1	35.3	36 4	37 5	38.1	38.8	39 6	40 3
45	33 9	34.7	35 9	37.0	38 0	38.7	39.4	40.2	41 0
50	34.4	35 3	36 5	37.6	38 6	39.3	40 0	40.8	41 7
55	35 0	35.9	37 1	38 2	39 2	39.9	40.7	41.5	42 3
7:00	35.7	36 5	37.6	38.7	39.7	40.5	41.4	42.2	43 0
05	36 2	37.0	38.2	39.3	40.3	41 1	42.0	42 9	43.7
10	36.8	37.6	38.8	39.9	40.9	41 7	42 6	43.5	44.4
15	37 3	38.2	39.4	40.5	41.5	42.4	43 3	44.2	45.1
20	37.9	38.7	40.0	41.1	42.1	43.1	44.0	44 9	45.8
25	38.4	39 3	40.6	41.7	42.7	43.7	44.7	45.6	46.5
30	39.0	39.9	41 2	42.3	43 3	44.4	45 4	46 2	47.1
35	39 7	40.5	41 8	42.9	44.0	45.1	46 0	46 9	47 8
40	40.2	41.1	42 3	43.5	44.7	45.7	46.7	47.6	48.4
45	40.8	41.7	42.9	44.1	45 3	46.4	47 3	48.3	49.1
50	41.4	42.2	43.6	44.9	46.1	47.2	48 0	48.9	49.8
55	42.0	42.8	44.2	45.5	46.8	47.9	48 7	49.6	50.5
8:00	42.6	43.5	44 9	46.2	47.4	48.5	49 4	50.3	51.2
05	43.1	44.2	45 5	46.8	48 0	49.1	50 1	51.0	51.9
10	43 7	44.9	46 2	47.5	48.7	49.8	50 8	51.7	52.6
15	44.3	45.6	46 9	48.2	49 4	50.5	51.5	52 4	53 3
20	45.0	46.2	47.6	48.9	50.1	51.2	52.2	53.1	54 0
25	45.7	46.9	48.3	49.6	50.8	51.9	52.9	53.8	54.7
30	46 4	47.6	48.9	50 2	51.5	52 6	53.6	54 5	55.3
35	47.1	48.3	49 6	50.9	52 1	53.3	54.3	55.2	56.0
40	47.7	49.0	50.3	51.6	52 8	53.9	55.0	55.9	56.7
45	48.4	49.6	50.9	52.2	53.5	54 6	55.6	56 5	57 4
50	49 0	50.3	51.6	52.9	54 1	55.2	56 3	57.2	58.1
55	49.7	51.0	52 3	53.6	54.8	55.9	57.0	58.0	58.9
9:00	50 4	51.7	53 0	54.3	55.5	56 5	57.7	58.7	59 6
05	51.1	52.4	53 7	55.0	56.2	57.3	58.4	59.5	60.4
10	51.8	53.1	54 4	55 7	56 9	58 0	59 1	60.2	61.2
15	52.5	53 8	55.1	56.4	57.7	58.8	59 9	61.0	61 9

TABLE 1—(*Continued*)

P–O (min.: sec.)	Focal depth in km.								
	25	100	200	300	400	500	600	700	800
9:20	53.2	54.5	55.8	57.1	58.4	59.6	60.7	61.8	62.7
25	53.9	55.2	56.6	57.9	59.1	60.3	61.5	62.6	63.5
30	54.6	55.9	57.3	58.6	59.9	61.1	62.3	63.4	64.3
35	55.3	56.6	58 0	59.3	60.6	61.9	63.1	64.2	65.1
40	56.0	57.3	58.7	60 0	61 3	62 6	63.9	65.0	65.9
45	56.7	57.9	59.4	60.8	62.1	63.4	64.7	65.8	66.7
50	57.3	58.6	60 1	61.5	62 9	64.3	65.5	66.6	67.5
55	57.9	59.3	60 8	62.3	63 7	65.1	66.3	67.4	68.3
10:00	58.6	60.0	61 6	63.1	64.6	65.8	67.1	68.2	69.1
05	59.3	60 7	62 4	63.9	65.3	66.6	67.9	69.0	70.0
10	60.0	61 4	63.1	64.7	66.1	67.4	68.7	69.8	70.9
15	60.7	62.2	63.9	65.5	66 9	68.2	69.5	70.7	71.9
20	61.4	62 9	64 6	66.3	67.8	69.0	70.3	71.6	72.8
25	62.1	63 6	65.4	67.1	68 6	69.9	71.2	72.5	73.8
30	62.9	64 3	66.1	67.8	69.4	70.8	72.1	73.4	74.8
35	63.7	65 0	66 9	68.6	70.2	71.7	73.0	74.3	75.7
40	64.4	65.8	67.7	69.4	71.1	72.6	73.9	75.3	76.7
45	65 2	66.5	68.4	70.2	72.0	73.5	74.8	76 2	77.6
50	66.0	67.3	69 2	71.0	72.8	74.4	75.8	77.2	78.6
55	66.7	68.1	70 0	71.9	73.7	75.3	76.7	78.1	79.5
11:00	67.5	68.9	70 9	72.8	74.6	76.2	77.6	79.0	80.4
05	68.3	69 7	71.7	73.7	75.5	77.1	78.6	80.0	81.4
10	69.1	70 5	72.6	74.6	76.5	78.1	79.6	81 0	82.4
15	70.0	71.4	73 5	75.5	77.4	79.0	80.5	82.0	83.5
20	70.8	72.2	74.4	76.4	78 3	80.0	81.5	83.0	84.5
25	71.7	73.1	75 2	77.2	79.1	80.9	82.5	84.0	85.6
30	72.6	74.0	76.1	78.1	80 0	81.9	83.5	85 1	86.7
35	73.5	74.9	77.0	79.0	81.0	82 8	84.5	86.1	87.8
40	74.4	75.8	77.9	79.9	81.9	83.8	85.5	87.2	88.9
45	75.2	76.7	78.8	80.9	82.9	84.7	86.5	88.3	90.1
50	76.1	77.6	79.8	81.9	83.9	85.7	87.6	89.4	91.3
55	77.0	78.5	80.7	82.8	84.8	86.7	88.6	90.5	92.4
12:00	77.8	79.4	81.6	83 8	85.8	87.8	89.7	91.5	93 5
05	78 7	80.3	82 6	84.8	86.9	88.8	90.8	92.7	94.7
10	79.6	81 2	83.6	85.9	87.9	89.9	91.9	93.9	95 8
15	80.6	82.2	84.6	86.9	89.0	91.1	93.1	95.0	96.9

TABLE 1—(*Concluded*)

P–O (min.: sec.)	Focal depth in km.								
	25	100	200	300	400	500	600	700	800
12:20	81.6	83.2	85.6	87.9	90.1	92.2	94.2	96.1	98.0
25	82.6	84.2	86.6	89 0	91 2	93.3	95.3	97.3	99.2
30	83.6	85.2	87.6	90.0	92.3	94.5	96.5	98.4	100.3
35	84.6	86.2	88.7	91.1	93.4	95.6	97.6	99.6	101.5
40	85.6	87.2	89.8	92.2	94.5	96.7	98.7	100.7	102.6
45	86.6	88.2	90.9	93.3	95.6	97.8	99.8	101.8	103.7
50	87.6	89.3	92.0	94.5	96.8	99.0	101.0	103 0	104.8
55	88.6	90.5	93.1	95.6	97.9	100.1	102.1	104.1	105.9
13:00	89.7	91.6	94.2	96.7	99.0	101.2	103.3	105.2	107.1
05	90.8	92.7	95 3	97.8	100.1	102.3	104.4	106.3	108.2
10	91.9	93.9	96.5	98.9	101.2	103.5	105.5	107.5	109.3
15	93.0	95.0	97.6	100.0	102.4	104.6	106.7	108.6	110.4
20	94.1	96.1	98.7	101.1	103.5	105.7	107.8	109.7	111.5
25	95.2	97.3	99.9	102 3	104.7	106.9	108.9	110.8	112.7
30	96.3	98.4	101.0	103.4	105.8	108 0	110.1		
35	97.5	99.5	102.1	104.6	106.9	109.1	111.2		
40	98.6	100.6	103.3	105.7	108.0	110.3			
45	99.7	101.7	104.4	106.8	109.2	111.5			
50	100.8	102.9	105.5	108.0	110.4				
55	101.9	104.0	106.6	109.1	111.5				
14:00	103.0	105.1	107.8	110.3					
05	104.1	106 2	108.9	111.5					
10	105 2	107.4	110.0						
15	106.1	108.5	111.1						
20	107.5	109 6	112.3						
25	108.6	110.7							
30	109.7								

TABLE 2

CHARACTERISTIC INTERVALS (MIN.:SEC.) OF S−P (UPPER SECTIONS OF TABLE) AND DIFFERENCES OF P FOR PAIRS OF STATIONS IN DEEP-FOCUS EARTHQUAKES (LOWER SECTIONS OF TABLE)

(a) South American shocks

Year Day Hour:minute	1929 May 25 11:59.6	1935 Dec. 14 1:31.2	1930 Aug. 4 5:04.5	1933 Aug. 29 14.52.6	1932 Dec. 9 8.34.9	1934 June 24 5:59.6	1933 Oct. 25 23:28.3	1936 Jan. 14 14:12.2	1934 Mar. 1 21:45.4
Latitude Longitude Depth in km.	8½ S 75½ W 150	9½ S 70½ W 650	9½ S 70½ W 650	11 S 69½ W 650	15 S 75 W 70	22 S 68½ W 100	23 S 66¾ W 220	29 S 62½ W 620	40 S 72½ W 120
Station—									
La Plata	4:52	4:09		3:42	3:28	2:40	2:22	1:29	2:23
Sucre	2:36	2:02					0:45	2:00	3:50
La Paz	1:54	1:38	1:34	1:27	1:14	1:18	1:22	2:09	4:09
Huancayo		1:12		1:17		2:15	2:26	2:20	4:38
San Juan		3:57		4:10	5:22	6:02	5:53		7:50
Capetown		9:26					8:53	8:10	9:00
Wellington						11:06	10:51		9:40
St. Louis	6:47	6:25	6:28	6:41	7:40	8:30	8:26	8:31	9:55
Fordham			6:24	6:35	7:40	8:27	8:22		10:00
Ottawa	7:18	6:52					8:48		10:23
Pasadena	7:55	7:40	7:41	7:47	8:34	9:22	9:25	9:21	10:32
San Fernando		8:55				10:13	9:56	9:27	
Cartuja	9:45	9:04	9:02	8:58		10:16		9:28	
Zürich			9:55			10:29	11:06		

Santiago-Huancayo					3:18	−0:12	−0:54		−4:07
La Plata-La Paz	3:34	2:35		3:03	3:37	1:50	−1:17	−1:13	−2:10
San Juan-La Plata		0:31		0:31	1:24	4:04	4:26		6:47
San Juan-La Paz		3:06		3:34	5:01	5:54	5:43		4:37
Wellington-Pasadena						1:35	1:36		−0:34
Christchurch-Pasadena						1:37		0:47	−0:38
Pasadena-Fordham			1:25	1:21	0:58	1:04	1:07		0:23
Pasadena-Ottawa	0:20	0:51				0:34	0:38		−0:01
San Fernando-Pasadena		1:23				0:54	0:40	0:09	1:06
Cartuja-Victoria		0:17	0:28	−0:18		−0:02			
Strasbourg-Pasadena	3:24	2:25	2:27				1:46		
Neuchâtel-Pasadena			2:22	2:19		1:56	1:43	1:14	
Pasadena-La Plata	3:23	4:54		4:48	5:13	7:58	8:20	9:33	9:26
Hong Kong-Pasadena				10:09		7:41	7:54	7:46	
Chiufeng-Pasadena		9:09		9:03		8:27	7:16	7:42	7:28
Manila-Pasadena		9:32	9:32	9:32		8:31	7:32	7:41	7:10

TABLE 2—(*Continued*)

(*b*) Tonga-Fiji region

Year / Day / Hour:minute	1935 Jan. 1 13:21.0	1935 July 15 14:13.6	1935 July 29 7:38.9	1933 Sept. 6 22:08.5	1934 Oct. 10 15:42.1	1934 Dec. 15 19:14.4	1932 May 26 16:09.7	1931 Oct. 18 4:30.5
Latitude / Longitude / Depth in km.	17½ S 174½ W 300	19½ S 178½ W 580	20¾ S 178 W 510	21½ S 179¾ W 600	23½ S 180 540	23½ S 179½ W 530	25½ S 179¼ E 600	26 S 180 500
Station—								
Wellington	4:06		3:17	2:48		2:59		2:27
Christchurch	4:36		3:28		3:15	3:16		3:01
Riverview	5:11	4:14	4:21	4:09		4:03	4:02	3:55
Amboina		6:56	7:03	6:59		6:58	6:55	6:36
Manila	8:54		8:30	8:19	8:24	8:30	8:25	
Batavia	9:26	8:40	8:53	8:37	8:40	8:40	8:32	8:41
Kobe	8:22	8:33	8:45	8:31	8:37	8:40		8:57
Mizusawa	8:57		8:27	8:30	8:37	8:43	8:48	8:59
Nagoya			8:37	8:42	8:33	8:40	8:47	
Hong Kong	9:33	9:11	9:21	9:09	9:10	9:14	9:19	9:24
Chiufeng	9:53	9:29	9:40	9:25	9:35	9:35		
Pasadena	9:09	9:19	9:29	9:17	9:32	9:36	9:59	9:36
Berkeley	9:02		9:16	9:17	9:31	9:31	9:40	9:42
Tucson			9:39	9:42	9:57	9:42		9:36

Wellington-Apia	4:17		1:53	1:27	0:52		0:24	0:15
Riverview-Christchurch	0:55		1:01		1:02	1:00	1:02	1:14
Riverview-Apia	5:30	3:10	3:16	2:45	2:20		1:50	1:53
Manila-Kobe	0:07		−0:03	−0:13	−0:17	−0:16		
Manila-Wellington	5:28		6:16	6:13	6:37	6:33	6:50	
Nanking-Riverview	5:08	5:49	5:52	5:58	6:07	6:13		
Pasadena-Manila	0:16	0:58	0:52	1:06	1:14	1:10	1:20	
Chiufeng-Pasadena	1:06	0:33	0:35	0:28	0:22	0:24	0:20	0:23
Pasadena-Wellington	5:44		7:08	7:19	7:51	7:43	8:10	8:21
Honolulu-Riverview	0:47		2:19	2:35	3:07		3:29	
Pasadena-Hong Kong		0:04	−0:01	0:14	0:17	0:17	0:25	0:25
Hamburg-Pasadena			7:33	7:22	7:17	7:19	7:13	7:13
Kew-Pasadena	8:00	7:38	7:36	7:25	7:21			7:18
Strasbourg-Pasadena	8:07	7:42	7:37	7:29	7:23		7:19	7:20
Zürich-Pasadena	8:09		7:44	7:30			7:20	7:24

TABLE 2—(*Continued*)

(*c*) New Hebrides, Solomon Islands, East Indies

Year Day Hour: minute	1931 Mar. 2 2:18.6	1928 Aug. 24 21:43.5	1935 June 24 23:23.2	1931 July 23 14:20.9	1932 Jan. 9 10:21.7	1931 Mar. 28 12:38.6	1934 June 29 8:25.3	1934 May 1 7:04.9
Latitude Longitude Depth in km.	22 S 172 E 110	15 S 168 E 220	15¾ S 167¾ E 140	6½ S 155 E 400	6¼ S 154½ E 380	7 S 129½ E 80	6¾ S 123¾ E 720	3½ N 97½ E 145
Region	New Hebrides			Solomon Islands		East Indies		
Station—								
Apia		2:59	4:21			7:32		
Wellington	3:38	4:29	4:59	5:22	5:53	7:03	7:05	
Christchurch				5:36	5:38			10:00
Riverview	3:51	4:07	3:49	4:04	4:11	5:26	5:04	
Adelaide	4:53	5:04	5:05	4:31	4:39	4:55	4:22	6:54
Melbourne	4:36		5:08	4:36	4:49	5:03	4:58	
Batavia		7:54	8:01		6:25	4:03	2:43	2:14
Bombay				9:40	9:39	8:15	6:52	3:50
Phu Lien	9:30	8:53	9:00	7:18	7:08	5:34		3:35
Hong Kong	8:45		8:29	6:47	6:29	5:42	4:17	5:03
Manila			7:35	5:42	5:31	4:02	3:08	5:18
Kobe		7:44	7:54	6:17	6:03	6:19	5:40	5:14
Mizusawa	8:43	7:50	8:01	6:34	6:11	6:43	6:16	4:57
Chiufeng	10:02		6:43	7:34	7:28	6:48	6:02	5:37
Honolulu			7:55	7:14	7:04			
Pasadena	10:35		11:16	10:38	10:26			

Wellington-Manila	−5:47	−3:40	−3:57	−0.15	−0:20	4:08	4:41	
Christchurch-Chiufeng	−7:10		−5:33		−2:10			4:45
Wellington-Batavia		−4:02	−4:32	−1:23	−1:20	4:17	5:29	
Phu Lien-Christchurch	6:49			2:08	1:34			−7:52
Chiufeng-Riverview	7:17		6:13	4:14	4:00	2:06	1:16	
Nanking-Adelaide			3:32				1:06	−3:10
Bombay-Chiufeng			2:16			1:35	1:03	
Honolulu-Manila	−1:16	0:05	−0:38	1:41				
Mizusawa-Melbourne	5:07	3:44	3:55	1:52	1:52	1:54	1:36	
Helwan-Pasadena	6:44		6:38			−0:59	−1:39	−7:54
Pasadena-Chiufeng	0:40		1:13		3:07		6:18	11:17
Pasadena-Hong Kong	1:33		2:02	4:08	4:15	8:11	8:34	13:33
Copenhagen-Pasadena	6:42			7:39	5:48	−0:36	−0:43	−6:20
Strasbourg-Pasadena	6:57		6:47	6:09	6:02	3:55	−0:22	−6:04
La Paz-Strasbourg		−0:15	−0:44	0.03	−0:02	1:10	5:09	−7:15

TABLE 2—(*Continued*)

(*d*) Philippine Islands, Marianne Islands, South of Japan

Year Day Hour: minute	1926 Oct. 30 13:46.6	1929 Apr. 8 10:16.9	1929 June 4 15:16.0	1931 Sept. 9 20:38.5	1933 Sept. 2 16:41.1	1932 Apr. 4 19:16.5	1928 Mar. 29 5:06.0
Longitude Latitude Depth in km.	123 E 9½ N 520	124½ E 7¾ N 610	124½ E 6½ N 380	145¾ E 19¼ N 180	138¾ E 29 N 410	138¾ E 29 N 410	138¼ E 31¾ N 410
Station—							
Manila		1:33	1:43	4:34	3:46	3:21	3:39
Hong Kong	1:52	2:47		4:44	3:44	3:42	3:43
Zikawei	3:23		3:55	4:24		2:27	2:00
Chiufeng					3:28	3:10	
Kobe		4:10	4:32		1:10		0:57
Nagoya		4:19		3:07	1:06	1:05	0:51
Mizusawa	4:56	4:28	5:03	3:41	1:40	1:37	1:27
Phu Lien			3:31	5:23	4:32		4:30
Batavia		3:26	3:27	6:27	6:22	6:21	6:24
Bombay		6:29	6:47	8:44			7:30
Riverview		6:21	6:20	7:16	8:06		
Adelaide		5:56		7:09	8:11		8:17
Melbourne		6:27		7:02	8:45		
Honolulu				6:40	7:26	7:30	7:22
Pasadena				10:04	9:40	9:45	9:44
Ksara		9:34				9:41	9:35
Tashkent		7:20	7:42	8:40	7:12	7:12	7:07
Kew					10:17		10:09

Manila-Hong Kong	−1:38	−1:35	−1:48	−0:48	−0:07	−0:06	−0:02
Chiufeng-Manila					−0:13	−0:19	
Phu Lien-Hong Kong		0:36	0:38	1:02	1:04		1:01
Batavia-Mizusawa		−1:51	−2:05	3:45	5:48	5:51	6:12
Bombay-Zikawei		3:45	3:48	5:40			6:23
Adelaide-Honolulu				0:02	1:48		1:43
Pasadena-Manila				7:12	7:14	7:14	7:14
Pasadena-Chiufeng					7:27	7:33	
Pasadena-Strasbourg				−1:23	−0:33	−0:33	−0:23
Pasadena-Nagoya				8:18	10:13	10:16	10:31
Pasadena-Ksara						− 0:01	0:05
La Paz-Pasadena				7:10	7:24	7:23	

TABLE 2—(*Concluded*)

(*e*) Region of Japan, eastern Siberia, and Kamchatka

Year Day Hour:minute	1931 June 29 16:43.2	1929 June 2 21:38.6	1931 Feb. 20 5:33.4	1930 Jan. 5 1:19.8	1929 Jan. 13 0:03.2	1930 Mar. 10 16:27.4	1934 Jan. 3 9:42.4
Longitude Latitude Depth in km.	136¾ E 34 N 360	137¾ E 34½ N 360	135½ E 44¼ N 350	154 E 49 N 140	154¾ E 49¾N 140	149 E 50 N 620	156½ E 52¾ N 280
Station—							
Manila	4:03		4:52	6:21		5:30	6:34
Hong Kong		3:48	4:18	6:07	6:01	5:09	6:11
Zikawei	2:22	2:20	3:04	4:52		4:00	4:56
Chiufeng	3:06		2:41				4:36
Kobe	0:38	0:40	1:46	3:41	3:53	2:54	3:52
Nagoya	0:39	0:36	1:44	3:30	3:36		3:46
Mizusawa	1:08	1:09		2:30	2:53	2:11	3:05
Phu Lien		4:32		6:38	6:49	6:00	
Batavia		6:35	7:25	8:51	8:57		9:00
Bombay		7:35	7:28	8:59	9:00	7:55	8:53
Riverview		8:32	9:31	10:12	10:06		10:13
Adelaide		8:37	9:31		10:03		10:23
Melbourne			9:48		10:32		
Wellington		9:43			10:56		
Honolulu		5:35			6:50		6:33
Pasadena	9:46	9:44	9:18	8:22	8:23	8:04	7:56
Sitka					6:02		5:32
Ottawa				9:21	9:22		
Ksara		9:33	8:55	9:55	9:53	8:58	9:51

Tashkent		7:01	6:28			6:45	
Uccle			9:14	9:31	9:23	8:48	9:06
Strasbourg			9:20		9:39	8:52	9:17
Manila-Hong Kong		0:09	0:42	0:28	0:19	0:31	0:29
Chiufeng-Manila	−0:59						−2:25
Phu Lien-Hong Kong		1:03		0:49	0:41	0:30	
Batavia-Mizusawa		6:42	7:23	7:44	7:42		7:22
Bombay-Zikawei		6:22	5:37	4:56	4:48	4:46	4:36
Pasadena-Manila	7:03	6:59	5:15	2:13	2:08	2:53	1:35
Pasadena-Chiufeng	8:02						4:00
Pasadena-Strasbourg		−0:19	0:05	− 1:25	−1:30	−0:51	−1:23
Sitka-Honolulu					−0:54		−1:15
Pasadena-Nagoya	10:53	10:55	9:06	5:58	5:47		5:20
Pasadena-Ksara		0:11	0:21	−1:44	−1:45	−1:00	−1:48
Fordham-Pasadena			1:08		1:44		1:35
St. Louis-Pasadena		1:02	0:53	1:14	1:12	1:01	1:09
Victoria-Manila		6:08			0:43		−0:02
Ottawa-Pasadena			0:50	1:20	1:17		1:09
La Paz-Pasadena	7:23	7:25	7:38	8:48	8:52	8:23	8:56

TABLE 3

DISTANCES Δ FOR SHOCKS IN THE FIJI REGION

(A: 1931, Oct. 18; B: 1932, May 26; C: 1934, Dec. 15; D: 1933, Sept. 6; E: 1931, April 3; F: aftershock of B, 1932, May 26, $22^h\,21^m\!.9$.)

Station	Azimuth		Δ from P–O and H					Differences in Δ				
	A	E	A	B	C	D	E	(a) B–A	(b) B–F	(c) B–C	(d) B–D	(e) E–D
Apia	39	57	14.5	13.6		11.1		−0.9	−0 5		2.5	
Wellington	195	190	15.9	15.7	18.7	19.8	21.6	−0.2	0.2	−3.0	−4 1	1.8
Christchurch	197		18.6	18.3	22 3			−0.3	0.1	−4.0		
Riverview	244	234	26.4	25.2	27.3	28 7	29.3	−1 2	1.0	−2.1	−3 5	0.6
Melbourne	239	231	32 2	31.3		34.8	35.6	−0.9			−3.5	0 8
Adelaide	244	239	37.0	36.4		39.3	39.3	−0.6			−2.9	0 0
Honolulu		30		51 2		47 8	47.6				3 4	−0 2
Amboina		280		52.1	53.6				0.7	−1.5		
Perth	248	244	56.2	56.3				0.1				
Manila		296		68.4	69.6	68.5	67.4		0.0	−1.2	−0 1	−1.1
Batavia	273	271	70.0	69 8	72.3	72.3	71.6	−0.2	−1.3	−2 5	−2.5	−0.7
Sumoto	322	322	74.1		71.7		68.6					
Sendai	329		74.1									
Kobe	322	322	74.1		72.5	70 7	69.0					−1 7
Mizusawa	330	330	74.8	72.5	72.5	70.8	69.4	−2.3		0.0	1.7	−1.4
Hong Kong	300	300	79.4	78 2	79 2	77.8	76.5	−1 2		−1.0	0.4	−1.3
Berkeley	41	43	83.6	83.1	82 0	80.1	80.1	−0.5	0 0	1.1	3.0	0.0
Pasadena	47	48	84.2	83 1	82 6	80.5	80 3	−1 1	−0.8	0.5	2.6	−0 2
Tinemaha	44	46	86.1	85.3	84.1	82.3	81.9	−0 8	−0 4	1.2	4.0	−0.4
Phu Lien	296		85.7			83.7						
Tucson		52		88.0	86.7	85.3	85.7		−0 2	1.3	2.7	0.4
Chiufeng	317	317	88.8	87 2	87.3	86.1	84.4	−1 6		−0.1	1 1	−1.7
Florissant		54		106.0		103.1	104.1				2.9	1.0
La Paz	114	114	100 5	100 8		104.6		0 3			−3 8	
Irkutsk	323	324	102.1	100 3			101.0	−1 8				

TABLE 4

CALCULATION OF DIFFERENCES BETWEEN EPICENTRAL DISTANCES Δ_1 CALCULATED BY USING ORIGIN TIME O AND DEPTH AND TRAVEL TIMES OF P; ALSO EPICENTRAL DISTANCES Δ_2 FROM AN ADOPTED APPROXIMATE EPICENTER, FOR THREE SHOCKS

Date of shock Adopted epicenter Adopted O Adopted depth		(a) 1931, Oct. 18 25.2° S, 179½° E $4^h 30^m 33^s$ 500 km.				(b) 1931, April 3 19° S, 180° $23^h 19^m 18^s$ 680 km.				(c) 1933, Sept. 6 21½° S, 179° W $22^h 08^m 29^s$ 600 km.			
Station	Azim. degree	Δ_2 degree	P−O min.:sec.	Δ_1 degree	$\Delta_1-\Delta_2$ degree	Δ_2 degree	P−O min.:sec.	Δ_1 degree	$\Delta_1-\Delta_2$ degree	Δ_2 degree	P−O min.:sec.	Δ_1 degree	$\Delta_1-\Delta_2$ degree
Apia	57	13.5	3:06	14.5	1.0					10.3	2:29	11.1	0 8
Wellington	190	16.8	3:21	15.9	−0.9	22.7	4:10	21.6	−1.1	20.4	3:56	19.8	−0.6
Christchurch	192	19 4	3:45	18.6	−0 8								
Riverview	234	26.9	4:59	26.4	−0.5	29.6	5:16	29.3	−0.3	29.0	5:14	28.7	−0.3
Melbourne	231	32.6	5:49	32 2	−0.4	35.8	6:10	35.6	−0.2	35.0	6:06	34.8	−0 2
Adelaide	239	37.3	6:31	37.0	−0 3	39.8	6:39	39.3	−0.5	39.4	6:44	39 3	−0.1
Honolulu	30					45.8	7:41	47.6	1.8	47.3	7:49	47.8	0 5
Perth	244	56.6	8:57	56 2	−0.4								
Manila	296					67.2	9:56	67 4	0.2	68.9	10:09	68.5	−0.4
Batavia	271	72 6	10:26	70.0	−2.6	72.2	10:21	71.6	−0.6	73.1	10:31	72.3	−0.8
Sumoto	322	73 6	10:48	74.1	0 5	68 5	10:04	68.6	0.1				
Sendai	329	73.6	10:48	74 1	0 5								
Kobe	322	73.7	10:48	74 1	0.4	68.5	10:06	69 0	0.5	70 8	10:22	70 7	−0.1
Mizusawa	330	74 2	10:52	74.8	0.6	68.6	10:08	69.4	0 8	70 9	10:23	70.8	−0 1
Hong Kong	300	80.0	11:17	79.4	−0.6	76.5	10:48	76.5	0.0	78.3	11:01	77.8	−0.5
Berkeley	43	82.8	11:39	83 6	0.8	78.6	11:07	80.1	1.5	79.6	11:13	80.1	0.5
Pasadena	48	83.1	11:42	84.2	1.1	79.3	11:08	80.3	1.0	80.1	11:15	80.5	0.4
Tinemaha	46	84.4	11:52	86 1	1.3	80 8	11:16	81.9	1.1	81.6	11:24	82 3	0.7
Phu Lien	296	85 2	11:50	85.7	0.5					83.9	11:31	83.7	−0.2
Tucson	52					83.7	11:35	85.7	2.0	84.3	11:39	85.3	1.0
Chiufeng	317	88.6	12:05	88.8	0.2	83.8	11:28	84.4	0.6	86 0	11:43	86.1	0.1
La Paz	114	101.2	12:57	100.5	−0.7					102.5	13:06	104.6	2.1
Irkutsk	324	101.8	13:04	102.1	0.3								
Huancayo	104									98.9	12:41	98.8	0.9
Florissant	54									102.1	12:57	103.1	1.0

Location of Epicenters

In the previous paper the methods for determining epicenters for deep shocks were largely independent of precise travel times, such as were given in the accompanying tables, the only important assumption being that of identical wave propagation in all azimuths. Such procedure is necessary to establish the travel times, and in part it is required for their revision. However, since the tabulated times of P agree very well with observation, the error for most distances and focal depths probably not exceeding two seconds, it is possible to assume these times as a basis, either for the revision of travel times of other phases or for the determination of epicenters.

A preliminary determination of the general location of the epicenter is facilitated by comparison with the data of shocks already investigated. Table 2 has been constructed for this purpose. The epicenters and depths given for these shocks are taken from a paper soon to be published.[4] The table is divided into regional sections, giving for the various shocks the observed S−P intervals at selected stations, and the time differences between the arrivals of P at selected pairs of stations. The stations used have been selected for their location with respect to the epicenters, the reliability of their reported times, or the early date of publication of their bulletins, or for a combination of these reasons. Data for recent and well-observed shocks have been preferred. The intervals given as S−P are as reported by the stations, even where it is probable that the observed phase is SKS. In the second section the first recorded phase has been used in each case, irrespective of whether it proves to be P or P′.

As an example of this procedure we may take the shock of January 5, 1937, at 11^h. The readings at Pasadena are:

iP	11	20	51
epP		22	36
iS		30	32
iSKPP′		49	35

These data give a distance of 85° and a depth of 470 km., with origin time 11:09.1. For the methods used, refer to the previous paper. At the time when the Pasadena bulletin was being prepared, we had already received data for the following stations, either directly or by way of Strasbourg:

				S−P
Nanking	P 12:54	S 15:49		2:55
Manila	P 13:23	S? 15:30		——
Chiufeng	P 13:30	i 15:47	S 16:45	3:15
Hong Kong	P? 13:38	S? 16:06	SS? 17:10	3:32
Phu Lien	iP 14:45	iS 19:08		4:23

[4] B. Gutenberg and C. F. Richter, "Depth and Geographical Distribution of Deep-Focus Earthquakes," a paper presented at the joint meeting of the Geological Society of America, Cordilleran Section, and the Seismological Society of America, at Berkeley, April 10, 1937.

The S−P intervals are tabulated as identified by comparison with the origin time determined at Pasadena. Since Nanking is the nearest station, with a travel time for P of 3.8 minutes, an origin in the Japanese region is suggested; the other stations confirm this with the foregoing interpretation of the readings. We now compare with sections (*d*) and (*e*) of table 2. Using the values of S−P for Chiufeng, Hong Kong, Phu Lien, and Pasadena ($9^m 41^s$), we find reasonable agreement with the last three columns under (*d*) and the first two under (*e*). To discriminate more closely we may make use of the time differences between P at pairs of stations. The best agreement is with the shock of September 2, 1933. We here tabulate the differences in the two cases for direct comparison:

	1937, Jan. 5	1933, Sept. 2
Manila-Hong Kong	−0:15	−0:07
Chiufeng-Manila	0:07	−0:13
Phu Lien-Hong Kong	1:07	1:04
Pasadena-Manila	7:18	7:14
Pasadena-Chiufeng	7:21	7:27

The differences Pasadena-Chiufeng and Chiufeng-Manila are definitely out of agreement with the data of the shocks in section (*e*).

Using all the data, the epicenter is found to be approximately 28° N, 138° E.

When the data of a considerable number of stations are available, such a comparison of shocks can be used for a precise determination of the relative positions of the epicenters. This requires that the origin times and depths be first determined to a good approximation, by the methods outlined in the previous paper. For any one station the distances corresponding to the travel times of P for two given shocks can be read off from table 1. The differences between these calculated distances can then be plotted as a function of the azimuth of the stations. No great precision is required in the azimuth, which can usually be taken with sufficient accuracy from one of the shocks in the same region tabulated in the International Summary.

Examples of the calculated difference in distance for a group of shocks in the Fiji-Tonga region are given in table 3. For shocks A, D, and E the values of P−O are given in table 4. The differences given in table 3 are plotted as functions of azimuth in figure 2.

The figure shows clearly that the calculated differences can be represented closely by properly drawn sine curves, as is to be expected. The equation of such a curve may be written $y-c=A \cos (x-a)$.

Here A, the amplitude of the sine function, is the distance between the two epicenters. The azimuth $x=a$ gives the maximum of y, and this determines the direction of the line joining the two epicenters. The constant c indicates that the curve is not symmetrical with respect to the zero line; this may be due either to a slightly incorrect origin time or to a slight error in the assumed focal depth, in one or both shocks. The correspondence between the effect of error in

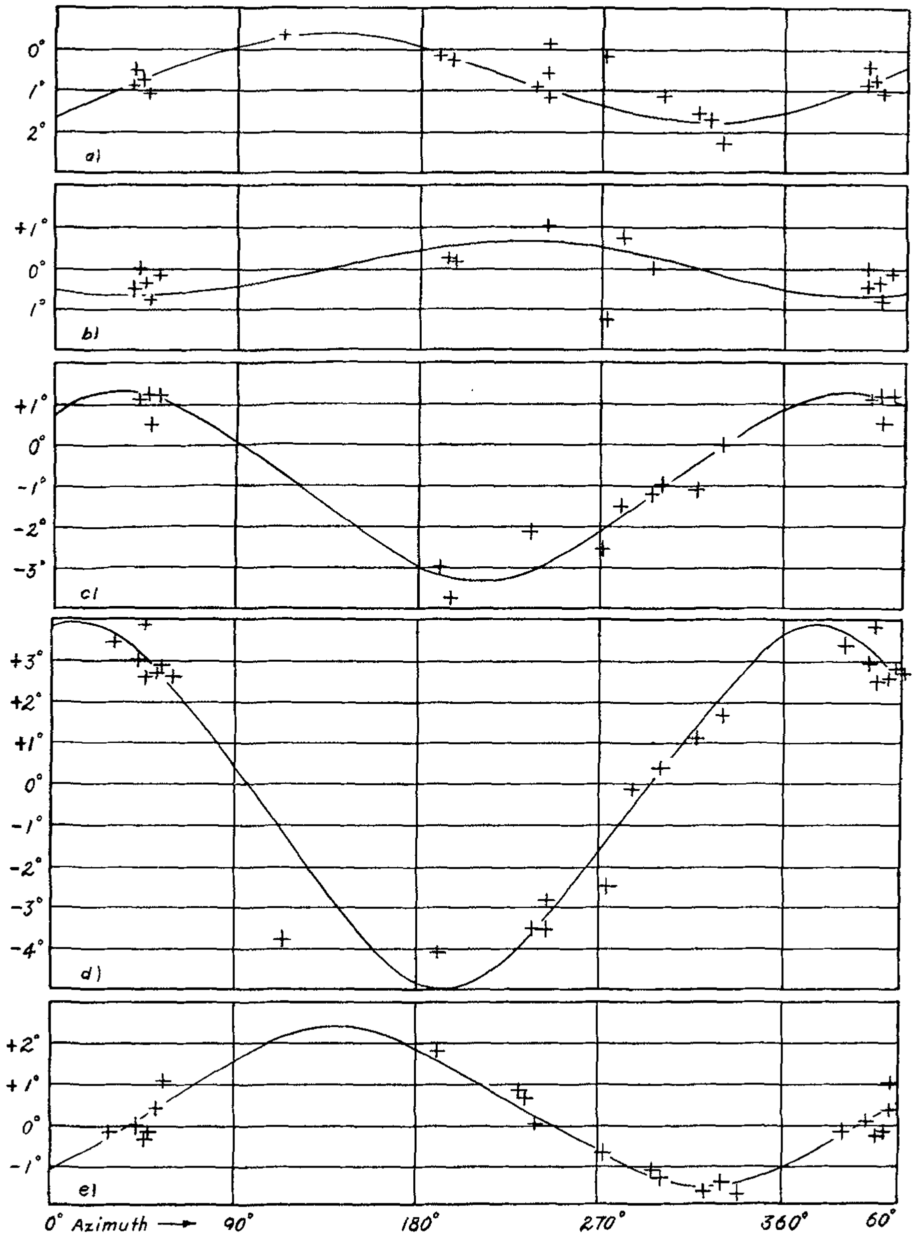

Fig. 2. Differences in epicentral distances for a group of shocks in the Fiji-Tonga region (see table 3), plotted as functions of azimuth.

origin and error in depth is exhibited in the following tabulation. If the assumed origin time is one second too late, then the calculated distances are too small by the amounts shown:

Distance (deg.)	Focal depth		
	100 km.	400 km.	700 km.
10....................	.07	.08	.12
30....................	.12	.12	.12
60....................	.14	.15	.15
90....................	.23	.23	.23

If the assumed depth is 10 km. too large, then the calculated distances are too large by the amounts shown:

Distance (deg.)	Focal depth		
	100 km.	400 km.	700 km.
10....................	+.01	.00	− 02
30....................	.12	+.10	+.04
60....................	.16	.12	.09
90....................	.26	.22	.19

If there is an error in the assumed depth or origin time, and most of the stations are at about the same distance, the result will be a vertical displacement of the curve drawn to represent the distance residuals. If there are available stations distributed over a considerable range of distance in about the same azimuth, the plotted residuals will show an effect of distance, directly suggesting a revision in depth or origin time. However, as the preceding tabulations show, except when there are a number of good stations at very short distances, it may not be possible to decide from these residuals alone whether the correction should be applied to the depth or to the origin time, or to both. In fact, if the assumed origin time is E seconds too late, and the assumed depth is also $10E$ kilometers too large, the two errors will very nearly compensate for all except the shortest distances. Thus a good agreement among the data does not necessarily mean that the depth and origin time are both correct. On the other hand, if the residuals show a large scatter about the mean sine curve, the error is more likely to be in the depth than in the origin time.

In most of these cases it will be observed that the location of the epicenter is not likely to be much affected, provided that the available stations are reasonably numerous and well distributed in azimuth.

By making use of the other principal recorded phases it appears possible to separate error in depth from error in origin time; this point requires further discussion, which is reserved for a later paper.

We may proceed to draw a few specific conclusions from the curves of figure 2. In the curve *a*) we have $A = 1°$ and $a = 140°$, approximately; consequently shock B is about 1° northwest of shock A. (For dates of shocks refer to table 3.)

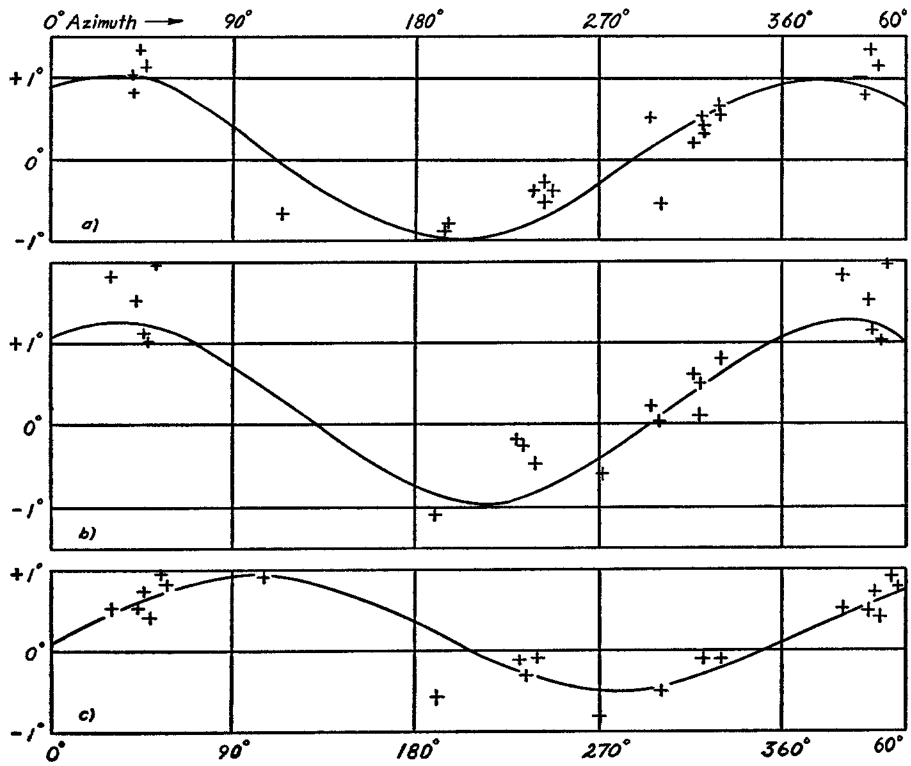

Fig. 3. Differences in epicentral distances, $\Delta_1 - \Delta_2$, plotted from table 4 as functions of azimuth.

We have $c = -\frac{1}{2}°$; this is probably due to a combination of small errors in the depths and origin times of the two shocks. The curve *b*) shows that the strongest aftershock of the large earthquake B originated within less than a degree from the main shock. The remaining three curves show that shock B originated about $2\frac{1}{2}°$ south and somewhat west of C, and $4\frac{1}{2}°$ south and slightly west of D, and that shock E originated about 2° northwest of D.

When no shock is available for comparison, or when it is desired to fix the absolute geographical position of the epicenter, a similar method can be used. As before, the depth and origin time are determined as precisely as possible, and the distances are determined from these by using table 1. These distances are then compared with distances calculated from an assumed approximate epicenter, and the residuals are plotted as functions of the azimuth. Table 4 and figure 3 give three examples of this procedure. For shocks *a*) and *b*) the epicenters given in the International Summary were taken as first approximations. For shock *c*) the distances were calculated from the adopted epicenter, using geocentric latitudes. The plotted curves indicate that shocks *a*) and *b*) are about 1° south of the International Summary epicenters, and that shock *c*) occurred about 1° west of the adopted epicenter.

By combining both methods, and using epicenters located carefully by the method of least squares, as in the previous paper, an entire group of epicenters can be located with precision, both absolutely and relatively. The epicenters given in table 2 have been corrected by these methods, and are the best we can give at present for these particular shocks.

BALCH GRADUATE SCHOOL OF THE GEOLOGICAL SCIENCES,
CALIFORNIA INSTITUTE OF TECHNOLOGY [Contribution No. 228].
PASADENA, CALIFORNIA.